Lafayette College
Department of Civil and Environmental Engineering

CE 321: Introduction to Environmental Engineering and Science **Fall 2019**

Homework #10
Due: Monday, 11/25/19
SOLUTIONS

1) If the BOD of a municipal wastewater at the end of 7 days is 60 mg/L and the ultimate BOD is 85.0 mg/L, what is the rate constant?

2) Assuming that the data in Problem 1 were taken at 25ºC, computer the rate constant at 16ºC.

3) A sample of municipal sewage is diluted to 1% by volume prior to running a BOD_5 analysis. After 5 days the oxygen consumption is determined to be 2.00 mg/L. What is the BOD_5 of the sewage?

4) If the BOD_5 values for two livestock wastes having *k* values of 0.3800 day^{-1} and 0.240 day^{-1} are16230.0 mg/L, what would be the ultimate BOD for each?

5) A wastewater has a five-day BOD equal to 210 mg/L (test performed at 20ºC) and an ultimate BOD of 350 mg/L. Find the five-day BOD at 25ºC.

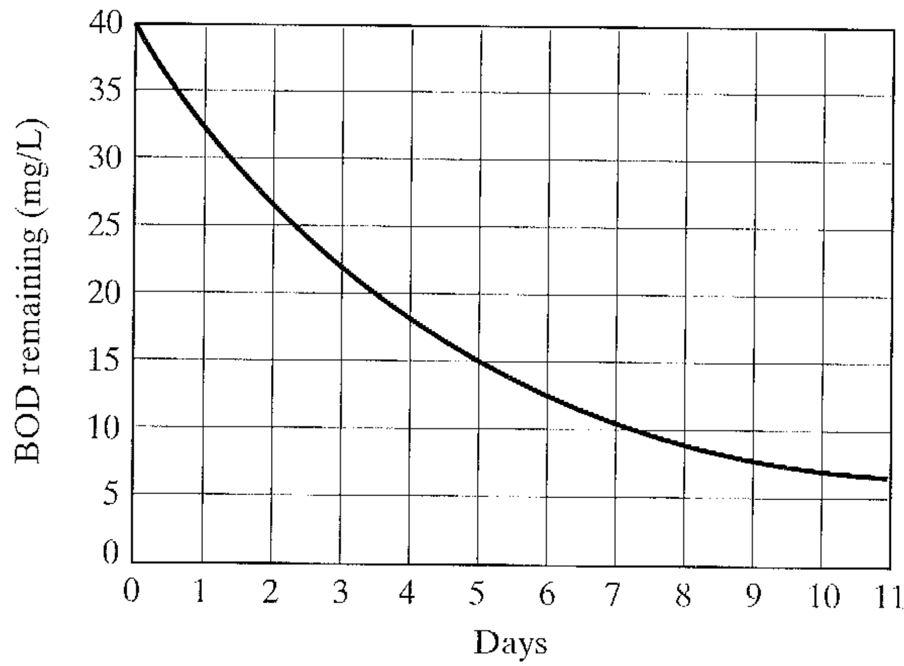
6) In a standard five-day BOD test,
   a. Why is the BOD bottle stoppered?
   b. Why is the test run in the dark (or in a black bottle)?
   c. Why is it usually necessary to dilute the sample?
   d. Why is it sometimes necessary to seed the sample?
   e. Why isn't ultimate BOD measured?
   f. What concentration of DO would you suggest as a starting concentration.

7) Assuming 0.1 mM of glutamic acid ($C_5H_9O_4N$) is used in the following stoichiometric reactions, calculate the Theoretical NBOD of glutamic acid.

$$C_5H_9O_4N + 4.5O_2 \rightarrow 5CO_2 + 3H_2O + NH_3$$
$$NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O$$

8) If the dissolved oxygen concentration measured during a BOD test is 9 mg/L initially, 6 mg/L after 5 days, and 3 mg/L after an indefinitely long period of time, calculate the 10-day BOD.

9) The following figure shows a plot of BOD remaining versus time for a sample of the effluent taken from a wastewater treatment plant.
   a. What is the ultimate BOD (L_o)?
   b. What is the five-day BOD?
   c. What is L_t for 7 days?



10) If the BOD_5 for some wastewater if 200 mg/L and the ultimate BOD is 300 mg/L, find the reaction rate constant k (base e) and K (base 10).

11) Suppose a wastewater has a BOD_5 equal to 180 mg/L and a reaction rate (k) equal to 0.22/day.
   a. Find the ultimate carbonaceous oxygen demand (CBOD).
   b. Find the remaining BOD after five days have elapsed.

12) Glutamic acid ($C_5H_9O_4N$) is used as one of the regent for a standard to check the BOD test. Determine the theoretical oxygen demand of 150 mg/L of glutamic acid. Assuming the following reactions:

$$C_5H_9O_4N + 4.5O_2 \rightarrow 5CO_2 + 3H_2O + NH_3$$
$$NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O$$

13) 10.0 ml sample of wastewater with enough water to fill a 300 ml bottle has an initial DO of 9.0 mg/L. To help assure an accurate test, it is desirable to have at least a 2.0 mg/L drop in DO during the five day run, and the final DO should be at least 2 mg/L. For what range of BOD_5 would this dilution produce the desired results. Assume this test to be a five-day, unseeded BOD test.

14) A water sample is diluted by a factor of 10 using ***seeded dilution water***. Dissolved oxygen concentration is measured at 1-d intervals, and the results are listed below. Using these data, determine the BOD as a function of time, i.e., calculate the BOD for each day.

Time, d	**Diluted Sample** Dissolved Oxygen, g/m^3	**Seeded Blank** Dissolved Oxygen, g/m^3
0	8.55	8.75
1	4.35	8.70
2	4.05	8.66
3	3.35	8.61
4	2.75	8.57
5	2.40	8.53
6	2.10	8.49
7	1.85	8.46

Name: Fanessa E de la Rosa
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1) If the BOD of a municipal wastewater at the end of 7 days is 60 mg/L and the ultimate BOD is 85.0 mg/L, what is the rate constant?

Given: $BOD_7 = 60 mg/L$ $t = 7 days$

$BOD_u = L_0 = 85. mg/L$

Find: Rate Constant $= k$

Solve:

$BOD_t = L_0(1 - e^{-kt})$

$1 - e^{-kt} = \frac{BOD_t}{L_0}$

$1 - \frac{BOD_t}{L_0} = e^{-kt}$

$-kt = \ln\left(1 - \frac{BOD_t}{L_0}\right)$

$-kt = \ln\left(1 - \frac{60 mg/L}{85 mg/L}\right)$

$\frac{-kt}{-t} = \frac{-1.22378}{-t}$

$k = \frac{-1.22378}{-7}$

$k = 0.1748 \rightarrow 1.748 \times 10^{-1}/day$

2) Assuming that the data in Problem 1 were taken at 25°C, computer the rate constant at 16°C.

Given: K_T @ 25°C = 0.1748/day $T_1 = 25$ °C $T_2 = 16$ °C

Find: K @ 16°C = ? $K_{20} = ?$

Solution:

$$K_T = K_{20}\,\theta^{(T_1-20)}$$

$$K_T = K_{20}\left(1.056^{(25-20)}\right)$$

$$K_{20} = \frac{0.1748}{1.313} = 0.133/\text{day}$$

$\theta = \begin{cases} 1.135 = 4° - 20°C \\ 1.056 = 20° - 30°C \end{cases}$

↓

$$K_{16} = K_{20}\,\theta^{(T_2-20)}$$

$$K_{16} = 0.133\left(1.135^{(16-20)}\right)$$

$$K_{16} = 0.08014/\text{day} \rightarrow \boxed{8.014\times10^{-2}/\text{day}}$$

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3) A sample of municipal sewage is diluted to 1% by volume prior to running a BOD_5 analysis. After 5 days the oxygen consumption is determined to be 2.00 mg/L. What is the BOD_5 of the sewage?

Given: $t = 5$ days 1% of BOD_5 = 2.00 mg/L → 1% of total volume

Find: Total volume of municipal sewage = ?

Solution:

2.00 mg/L (99%) = 198 mg/L

198 mg/L + 2 mg/L = 200 mg/L

$BOD_5 = 200$ mg/L

4) If the BOD_5 values for two livestock wastes having *k* values of 0.3800 day^{-1} and 0.240 day^{-1} are16230.0 mg/L, what would be the ultimate BOD for each?

Given : $k_1 = 0.3800\ day^{-1}$ $k_2 = 0.240\ day^{-1}$ $BOD_5 = 16230.0\ mg/L$

Find : BOD_u for each or L_0

Solution :

$$BOD_5 = L_0 (1 - e^{-k(5)}) \rightarrow L_0 = \frac{BOD_5}{(1 - e^{5k})}$$

① $k_1 = 0.3800\ day^{-1}$

$$L_0 = \frac{16230.0 mg/L}{(1 - e^{[5(0.3800)]})} = \boxed{19{,}084.43\ mg/L}$$

② $k_2 = 0.240\ day^{-1}$

$$L_0 = \frac{16230.0\ mg/L}{(1 - e^{[5(0.240)]})} = \boxed{23{,}225.34\ mg/L}$$

5) A wastewater has a five-day BOD equal to 210 mg/L (test performed at 20°C) and an ultimate BOD of 350 mg/L. Find the five-day BOD at 25°C.

Given: $t = 5$ days $BOD_5 = 210$ mg/L @ 20 °C $L_0 = BOD_u = 350$ mg/L

Find: $K_{20} = ?$ $K_{25} = ?$ BOD_5 @ 25 °C = ?

Solution:

① $BOD_t = L_0(1 - e^{-Kt})$

$$\frac{BOD_t}{L_0} = 1 - e^{-Kt}$$

$$e^{-Kt} = 1 - \frac{BOD_t}{L_0}$$

$$K = \frac{\ln\left(1 - \frac{BOD_t}{L_0}\right)}{-t}$$

$$K_{20} = \frac{\ln\left(1 - \frac{210 \text{ mg/L}}{350 \text{ mg/L}}\right)}{-5}$$

$$K_{20} = 0.1833 \text{ day}^{-1} \text{ @ } 20\,°C$$

② $K_T = K_{20}\,\theta^{(T-20)}$ — 4–20°C = 1.135; 20°–30°C = 1.056

$$K_{25} = 0.1833 \text{ day}^{-1}(1.056)^{(5)}$$

$$K_{25} = 0.2407 \text{ day}^{-1}$$

③ $BOD_5 \text{ @ } 25\,°C = L_0(1 - e^{-5K})$

$$BOD_5 \text{ @ } 25\,°C = 350 \text{ mg/L}\left(1 - e^{-5(0.2407 \text{ day}^{-1})}\right)$$

$$\boxed{BOD_5 \text{ @ } 25\,°C = 244.95 \text{ mg/L}}$$

6) In a standard five-day BOD test,
   a. Why is the BOD bottle stoppered?
   b. Why is the test run in the dark (or in a black bottle)?
   c. Why is it usually necessary to dilute the sample?
   d. Why is it sometimes necessary to seed the sample?
   e. Why isn't ultimate BOD measured?
   f. What concentration of DO would you suggest as a starting concentration.

Solution:

a.) The BOD bottle is stoppered because it prevents air from entering the bottle and disrupting the experiment's closed system.

b.) The test is run in the dark (or in a black bottle) because sunlight promotes growth in organics. Therefore, sunlight is not let in.

c.) It's usually necessary to dilute the sample because it encourages a more "controlled" environment. Dilutions are typically between 2-9 mg/L of dissolved oxygen.

d.) Sometimes it's necessary to seed the sample because it corrects the demand of the source seed. It is necessary to have a population of microorganisms that can consume the biodegradable organic matter present in the sample to determine BOD.

e.) Ultimate BOD isn't measured because it takes a long time in comparison to the standardized BOD test.

f.) I would suggest 9 mg/L as the starting concentration of DO since it is the maximum.

7) Assuming 0.1 mM of glutamic acid ($C_5H_9O_4N$) is used in the following stoichiometric reactions, calculate the Theoretical NBOD of glutamic acid.

$$C_5H_9O_4N + 4.5O_2 \rightarrow 5CO_2 + 3H_2O + NH_3$$

$$NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O$$

Find : Theoretical NBOD = ?

Solution :

$$NBOD = 4.57 \frac{mg\ O_2}{mg\ N} \quad (TKN\ as\ N)$$

$$M = \frac{conc}{MW} \rightarrow conc = M(MW)$$

$$0.1\ mM\ \text{glutamic acid} \cdot \frac{1\ mol\ NH_3}{1\ m\ of\ \text{glutamic acid}} = 0.1\ mM\ NH_3$$

If we need O_2 then :

$$0.1\ mM\ NH_3 \cdot \frac{2\ mol\ O_2}{1\ mol\ NH_3} = 0.2\ mM\ O_2$$

$$conc = M(MW)$$

Theo. NBOD → $conc\ of\ O_2\ needed = 200\ M\ O_2\ (32\ g/mol)$

$$= 6400\ g/L \rightarrow \boxed{6.4\ mg/L}$$

Name Faressa E de la Rosa
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8) If the dissolved oxygen concentration measured during a BOD test is 9 mg/L initially, 6 mg/L after 5 days, and 3 mg/L after an indefinitely long period of time, calculate the 10-day BOD.

Given: $BOD_1 = 9 mg/L$, $t = 0$; $BOD_2 = 6 mg/L$, t = after 5 days ; $BOD_3 = 3 mg/L$, $t_3 = \infty$

Find: $BOD_{10} = ?$

Solution:

$$BOD_{10} = L_0 \left(1 - e^{-kt}\right) \quad (t \to 10)$$

$L_0 \to BOD_u$

$$BOD_5 = 9 mg/L - 6 mg/L = 3 mg/L$$

$$L_0 = BOD_u = 9 mg/L - 3 mg/L = 6 mg/L$$

$$K_5 = \frac{\ln\left(1 - \frac{BOD_5}{L_0}\right)}{-t}$$

$$K_5 = \frac{\ln\left(1 - \frac{3 mg/L}{6 mg/L}\right)}{-5} = \boxed{0.1386 \ day^{-1}}$$

→ no change w/ days only temperature

$$BOD_{10} = L_0\left(1 - e^{-10K}\right)$$

$$= 6.0 mg/L \left(1 - e^{(-10 \cdot 0.1386 \ day^{-1})}\right)$$

$$\boxed{BOD_{10} = 4.50 \ mg/L}$$

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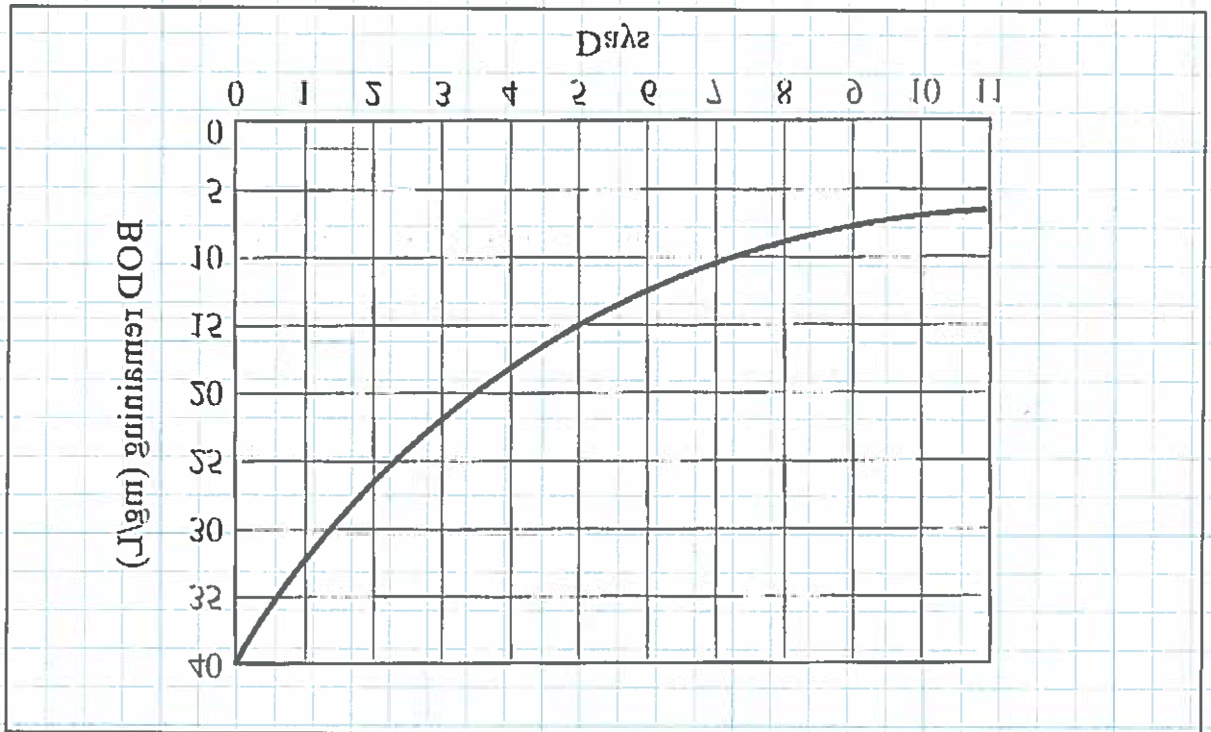
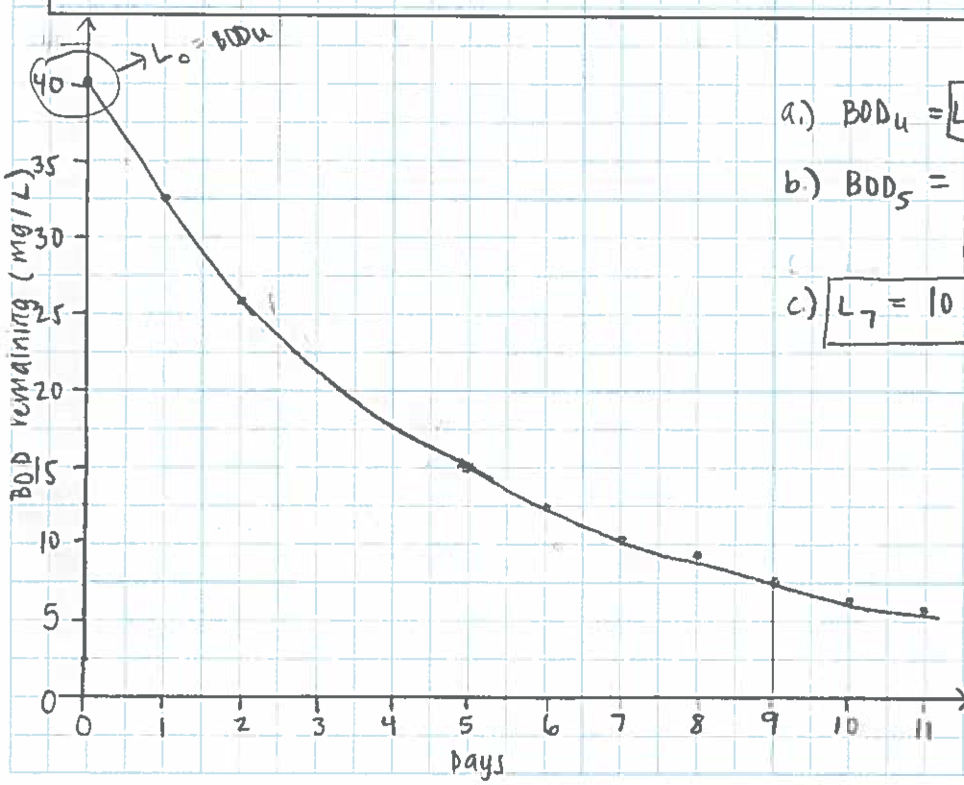
9) The following figure shows a plot of BOD remaining versus time for a sample of the effluent taken from a wastewater treatment plant.

a. What is the ultimate BOD (L_o)?
b. What is the five-day BOD?
c. What is L_t for 7 days?





a.) $BOD_u = L_0 = 40 mg/L$

b.) $BOD_5 = L_0 - L_t = 40 mg/L - 15 mg/L$

$BOD_5 = 25 mg/L$

c.) $L_7 = 10 mg/L$

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10) If the BOD_5 for some wastewater if 200 mg/L and the ultimate BOD is 300 mg/L, find the reaction rate constant k (base e) and K (base 10). → log instead of ln

Given: $BOD_5 = 200\ mg/L$ $L_0 = BOD_u = 300\ mg/L$

Find: ① K(base e) = ? ② K(base 10) = ?

Solution:

①

$$BOD_5 = L_0 (1 - e^{-5K})$$

$$K_5 = \frac{\ln\left(1 - \frac{BOD_5}{L_0}\right)}{-t}$$

$$K_5 = \frac{\ln\left(1 - \left(\frac{200\ mg/L}{300\ mg/L}\right)\right)}{-5}$$

$$\boxed{K_{5\,(base\ e)} = 0.2197\ day^{-1}}$$

②

$$BOD_5 = L_0 (1 - 10^{-5K})$$

$$K_5 = \frac{\log\left(1 - \frac{BOD_5}{L_0}\right)}{-t}$$

$$K_5 = \frac{\log\left(1 - \left(\frac{200\ mg/L}{300\ mg/L}\right)\right)}{-5}$$

$$\boxed{K_{5\,(base\ 10)} = 0.0954\ day^{-1}}$$

11) Suppose a wastewater has a BOD_5 equal to 180 mg/L and a reaction rate (k) equal to 0.22/day.

a. Find the ultimate carbonaceous oxygen demand (CBOD).
b. Find the remaining BOD after five days have elapsed.

Given: $BOD_5 = 180\ mg/L$ $K = 0.22/day$

Find: a) $L_0 = CBOD_u = ?$ b.) Remaining BOD = ?

Solution:

a.) $BOD_5 = L_0(1-e^{-kt})$

$$L_0 = \frac{BOD_5}{(1-e^{-kt})} = \frac{180 mg/L}{1-e^{(-0.22 \cdot 5)}}$$

$$\boxed{L_0 = 269.81\ mg/L}$$

b.) Remaining $BOD_5 = L_t + NBOD$

$$L_t = L_0 e^{-kt}$$

$$L_t = (269.81 mg/L)\, e^{(-0.22 \cdot 5)}$$

$$L_t = 89.81\ mg/L$$

Good

Remaining $BOD_5 = L_t + \left[\left(\frac{4.57\ mg\ O_2}{mg\ N}\right)(x\ mg\ N)\right]$

Remaining $BOD_5 = 89.81\ mg/L + NBOD$

$= 89.81\ mg/L + \left[\left(\frac{4.57\ mg\ O_2}{1\ mg\ N}\right)(x\ mg\ N)\right]$

↓ not given enough information to solve ✓

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12) Glutamic acid ($C_5H_9O_4N$) is used as one of the regent for a standard to check the BOD test. Determine the theoretical oxygen demand of 150 mg/L of glutamic acid. Assuming the following reactions:

$$C_5H_9O_4N + 4.5O_2 \rightarrow 5CO_2 + 3H_2O + NH_3$$
$$NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O$$

Given: BOD of $C_5H_9O_4N$ = 150 mg/L

Find: Theoretical Oxygen Demand = ?

Solution:

THOD = CBOD + NBOD

$\rightarrow \frac{150\ mg\ C_5H_9O_4N}{1\ L}\left(\frac{4.5\ mol\ O_2}{1\ mol\ C_5H_9O_4N}\right)\left(\frac{32\ g\ O_2}{mol}\right)\left(\frac{1\ mol\ C_5H_9O_4N}{147\ g}\right) = 146.9\ \frac{mg\ O_2}{L}$

$\rightarrow \frac{150\ mg\ C_5H_9O_4N}{1\ L}\left(1\ mol\ NH_3\right)\left(\frac{17\ g\ NH_3}{mol}\right)\left(\frac{1\ mol\ C_5H_9O_4N}{147\ g}\right) = 17.35\ \frac{mg\ NH_3}{L}$

$\hookrightarrow \frac{17.35\ mg\ NH_3}{1\ L}\left(2\ mol\ O_2\right)\left(\frac{32\ g\ O_2}{1\ mole}\right)\frac{1\ mol\ NH_3}{17\ g} = 65.317\ mg/L\ NH_3$

THOD = $\left(146.9\ \frac{mg\ O_2}{L}\right) + 65.317\ mg/L$

$\boxed{212.18\ \frac{mg\ O_2}{L}}$

13) 10.0 ml sample of wastewater with enough water to fill a 300 ml bottle has an initial DO of 9.0 mg/L. To help assure an accurate test, it is desirable to have at least a 2.0 mg/L drop in DO during the five day run, and the final DO should be at least 2 mg/L. For what range of BOD_5 would this dilution produce the desired results. Assume this test to be a five-day, unseeded BOD test.

Given: $DO_i = 9.0\ mg/L$ 10.0 mL water and 300 mL in natural

$DO_f = 2.0\ mg/L$

Find: range of BOD_5 = ? (between 9 and 2 mg/L)

Solution: Bottle Test. (unseeded)

$$BOD = \frac{DO_i - DO_f}{P} \rightarrow P = \text{Dilution factor} = \frac{\text{Vol sample}}{\text{Vol S} + DI_{H_2O}}$$

$$BOD_5 = \frac{9\ mg/L - 2\ mg/L}{(10\ mL / 300\ mL)} = 210\ mg/L$$

$$BOD_5 = \frac{9\ mg/L - 7\ mg/L}{(10\ mL / 300\ mL)} = 60\ mg/L$$

} Range

This dilution would produce the desired results from the range of 60 mg/L to 210 mg/L BOD_5.

14) A water sample is diluted by a factor of 10 using ***seeded dilution water***. Dissolved oxygen concentration is measured at 1-d intervals, and the results are listed below. Using these data, determine the BOD as a function of time, i.e., calculate the BOD for each day.

Time, d	**Diluted Sample** Dissolved Oxygen, g/m^3	**Seeded Blank** Dissolved Oxygen, g/m^3
0	8.55	8.75
1	4.35	8.70
2	4.05	8.66
3	3.35	8.61
4	2.75	8.57
5	2.40	8.53
6	2.10	8.49
7	1.85	8.46

Given: · chart

· P = dilution factor = 0.1

Find: BOD as a function of time for each day

Solution:

$$BOD = \frac{(DO_i - DO_f) - (DO_{Bi} - DO_{Bf})f}{P}$$

$f = \frac{90\% \text{ of seed diluted}}{100\% \text{ of seed water in sample}}$

$f = 0.9$

Day 1: $\frac{(8.55\ g/m^3 - 4.35\ g/m^3) - (8.75\ g/m^3 - 8.70\ g/m^3)\,0.9}{0.1} = 41.55$

Day 2: $\frac{(8.55\ g/m^3 - 4.05\ g/m^3) - (8.75\ g/m^3 - 8.66\ g/m^3)\,0.9}{0.1} = 44.19\ mg/L$

Day 3: $\frac{(8.55\ g/m^3 - 3.35\ g/m^3) - (8.75\ g/m^3 - 8.61\ g/m^3)\,0.9}{0.1} = 50.74\ mg/L$

Day 4: $\frac{(8.55\ g/m^3 - 2.75\ g/m^3) - (8.75\ g/m^3 - 8.57\ g/m^3)\,0.9}{0.1} = 56.38\ mg/L$

Day 5: $\frac{(8.55\ g/m^3 - 2.40\ g/m^3) - (8.75\ g/m^3 - 8.53\ g/m^3)\,0.9}{0.1} = 59.52\ mg/L$

Day 6: $\frac{(8.55\ g/m^3 - 2.10\ g/m^3) - (8.75\ g/m^3 - 8.49\ g/m^3)\,0.9}{0.1} = 62.16\ mg/L$

Day 7: $\frac{(8.55\ g/m^3 - 1.85(g/m^3)) - (8.75\ g/m^3 - 8.46\ g/m^3)\,0.9}{0.1} = 64.39\ mg/L$